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MESSENGER Observations of Magnetic Reconnection in Mercury’s Magnetosphere

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Solar wind energy transfer to planetary magnetospheres and ionospheres is controlled by magnetic reconnection, a process that determines the degree of connectivity between the interplanetary magnetic field (IMF) and a planet’s magnetic field. During MESSENGER’s second flyby of Mercury, a steady southward IMF was observed and the magnetopause was threaded by a strong magnetic field, indicating a reconnection rate ~10 times that typical at Earth. Moreover, a large flux transfer event was observed in the magnetosheath, and a plasmoid and multiple traveling compression regions were observed in Mercury’s magnetotail, all products of reconnection. These observations indicate that Mercury’s magnetosphere is much more responsive to IMF direction and dominated by the effects of reconnection than that of Earth or the other magnetized planets.

The two flybys of Mercury by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft have provided an opportunity to study a magnetosphere formed by solar wind interaction with a dipolar planetary magnetic field under solar wind conditions substantially different from those seen at Earth (1–3). When the interplanetary magnetic field (IMF) is brought into contact with the outer boundary of a magnetosphere [the magnetopause (MP)], and the angle between the two fields is between 90° and 270°, a magnetic X-line (also called a neutral line) will form, across which

![Fig. 1. Schematic of Mercury’s magnetosphere under southward IMF conditions as observed by MESSENGER on 6 October 2008. Note the strong magnetic field normal to the dayside MP, the large FTEs, and the reconnection line in the near-tail region, leading to plasmoid ejection and sunward-(SN) and anti-sunward–moving (NS) TCRs. These features were not seen during MESSENGER’s first Mercury flyby under northward IMF (17).](image-url)
the flux tubes reconnect (4, 5). This process of reconnection converts an interplanetary flux tube and a magnetospheric flux tube into two flux tubes, each with one end connected to the solar wind and the other rooted in the planet. This new magnetic field topology results in a solar wind and the other rooted in the planet. Such magnetic field lines may be regarded as electrodynamic “brushes” that tap the − v × B∞ electric field in the planetary frame of reference, where v is the solar wind flow velocity past the magnetosphere. In this manner, MP reconnection transfers solar wind energy into the magnetosphere, where, at Earth, it drives high-speed plasma flow, accelerates energetic charged particles, and powers magnetic storms.

Reconnection also occurs between the north and south lobes of planetary magnetotails (Fig. 1), especially after episodes of MP reconnection that increase the intensity of these tail magnetic fields (6). The circulation of plasma, magnetic flux, and energy from the X-line at the dayside MP to the nightside X-line in the cross-tail current layer and, later, back to the dayside magnetosphere constitutes the Dungey cycle that powers Earth-type magnetospheres (4).

Additional complexities are introduced when multiple X-lines form simultaneously at the MP or in the cross-tail current layer (7). The reconfiguration of the magnetic fields under these conditions produces magnetic flux ropes in addition to enhanced magnetic fields normal to the current sheet. These bundles of twisted magnetic flux are carried off by fast flow, comparable to the local Alfvén speed, away from the X-lines. At the MP, such flux ropes are called flux transfer events (FTEs) (8). However, in planetary magnetotails they are usually called plasmoids when they are transported sunward (9–12) or simply flux ropes when they are transported sunward back toward the planet (13). Numerical simulations of reconnection in Mercury’s magnetosphere predict the formation of all of these types of flux ropes, as is the case at Earth (14). The signatures of these magnetic structures as they move over a spacecraft are strong functions of how close the probe passes to the center of the flux ropes. For their helical nature to be observed, it is necessary that the spacecraft pass relatively close to the central axis of the flux rope (8, 13). Outside of the flux rope, magnetic field draping and compression result in readily observable perturbations known as traveling compression regions (TCRs) (15). The sense of the relative change in the north-south component of the tail lobe magnetic field that drapes over the flux ropes to form the TCR [north to south (NS) or south to north (SN)] indicates that the direction of motion of the underlying flux rope is anti-sunward or sunward, respectively. Although TCRs do not provide information on the internal structure of the flux ropes, they do signal the passage of these structures and provide estimates of their dimensions, location, and frequency of occurrence (15).

During the first MESSENGER flyby of Mercury on 14 January 2008, the IMF was generally northward and therefore unfavorable to reconnection between the IMF and the planetary magnetic field (16). Indeed, no evidence for magnetic reconnection between the IMF and the planetary magnetic field was observed except for some FTEs seen after brief southward excursions of the IMF when MESSENGER was outside the magnetosphere (17). Here we present measurements of magnetic reconnection and its effects on Mercury’s magnetosphere, taken by the MESSENGER Magnetometer (MAG) (18).

![Fig. 2. Overview of magnetospheric measurements taken by the MAG during MESSENGER’s second Mercury flyby. The magnetic field is displayed in the MSO coordinate system, defined as X MSO directed from the center of the planet toward the Sun, Z MSO normal to Mercury’s orbital plane and positive toward the north celestial pole, and Y MSO positive in the direction opposite to orbital motion. The longitude angle of the magnetic field is defined to be 0° toward the Sun and increases counterclockwise looking down from the north celestial pole. The magnetic field latitude angle is 90° when directed northward and 0° when it is in the X MSO–Y MSO plane. The root mean square (RMS) variance is calculated over 3-s intervals. CA was at an altitude of 199.4 km at 08:40:22 UTC, very near local midnight (00:04 local time).](www.sciencemag.org)
during the spacecraft’s second Mercury flyby on 6 October 2008.

MESSENGER’s second flyby was, like the first, near-equatorial, but the spacecraft approached and entered the magnetosphere farther downstream than in the previous encounter (Fig. 1). The inbound and outbound bow shock crossings were at 07:19:25 and 08:53:13 UTC, respectively. The inbound and outbound MP crossings were at 08:11:57 and 08:49:11. When MESSENGER passed into Mercury’s magnetotail (Fig. 2), there was a reduction in high-frequency magnetic fluctuations, a rapid increase in magnetic field intensity, and a rotation in the orientation of the field to a near-anti-sunward orientation (that is, at a longitude angle near 180°), indicating that the spacecraft entered through the downstream MP into the south lobe of the magnetotail.

About 30 s after entering the tail, a large-amplitude NS variation in the magnetic field lasting 4 s, followed by a longer recovery back to $B_z \sim 0$ [where $X$, $Y$, and $Z$ are defined in the Mercury solar orbital (MSO) coordinate system (Figs. 1 and 2)], is seen at the latitude angle of the field (Figs. 2 and 3A). This pattern is the signature of a plasmoid (9). High-time-resolution magnetic field measurements (Fig. 3A) show only a brief decrease in the total field magnitude just before and during the first half of the NS $B_z$ variation and only a weak $B_y$ enhancement, indicating only a shallow penetration into the plasmoid. After the plasmoid encounter, a series of five NS TCRs was observed between 08:13:30 and 08:17:00 UTC. The times between TCRs were ~0.1 to 1 min, and their durations were ~2 to 10 s (Figs. 2 and 3B). Remarkably, no energetic protons or electrons above 36 keV were measured by MESSENGER (19) in association with these TCRs. The transition from the impulsive energetic particle events reported by Mariner 10 during its first flyby, when the IMF was intermittently southward (I), to the TCRs observed by MESSENGER occurred near $X_{\text{MSO}} \sim -2.6 R_M$ (Fig. 2), implying that this is the mean location of the near-Mercury neutral line (NMNL). At Earth, the corresponding near-Earth neutral line (NENL) distance is $\sim -25 R_E$ (21). If the scaling factor of ~7 to 8 that has been found to map spatial structures in Mercury’s magnetosphere to that of Earth (I) is applied, then the NMNL is about 20% closer to Mercury than would be expected on the basis of its Earth analog.

No further plasmoids or TCRs were observed until seven SN TCRs were observed between 08:23:06 and 08:32:04 UTC (Fig. 2). Like the earlier NS TCRs, these SN TCRs were identified on the basis of the compression in the total field and the correlated SN perturbation in the relative $B_Z$ component (Fig. 3C). The times between the SN TCRs were comparable to those of the NS TCRs, but their individual durations were slightly shorter.

At Earth (13, 20, 27), Jupiter (11), and Saturn (12), plasmoids move down the tail with mean speeds of ~500 km/s. If a similar antisunward speed is assumed for the plasmoid observed by MESSENGER, then a diameter of ~0.8 $R_M$ (where $R_M$ is Mercury’s radius, 2440 km) is implied. Relative to the dimensions of their respective magnetospheres, the plasmoids at Mercury and Earth appear similar in size, with diameters that are ~10% of the diameters of their magnetic tails. The transition from NS to SN TCRs observed by MESSENGER occurred during the spacecraft’s second Mercury flyby on 6 October 2008.

Fig. 3. Magnetic field observations of (A) a NS plasmoid 4 s in duration at $X_{\text{MSO}} \sim -3.2 R_M$; (B) a NS TCR 8 s in duration at $X_{\text{MSO}} \sim -3.1 R_M$; and (C) a pair of SN TCRs, each 2 s in duration and separated in time by ~30 s, at $X_{\text{MSO}} \sim -1.8 R_M$. 

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minimum variance direction, $B_1$, was $-13$ nT (Fig. 4B), and a large, $\sim180^\circ$ rotation takes place in the plane of intermediate and maximum variance; i.e., $B_2$ and $B_3$ (Fig. 4C). These signatures are well known from studies of Earth’s MP (3, 8) and indicate that reconnection was taking place at an X-line located northward of the MESSENGER trajectory. In contrast, magnetic field measurements from the first MESSENGER flyby during northward IMF indicated that the structure of the dayside MP was a tangential discontinuity with a near-zero mean normal magnetic field (17).

The rate of reconnection is directly proportional to the ratio of the normal component of the magnetic field to the total field (5). Typical normal magnetic field components at Earth’s MP for southward IMF are $\sim0.5$ to 1 nT, and the ratio is $\sim1\%$. For the MP at Mercury, this ratio is $13$ nT/100 nT = $13\%$, or about an order of magnitude greater than the typical value at Earth. Enhanced rates of MP reconnection at Mercury have been predicted because of the increase in interplanetary Alfvén speed with distance from the center of the planet to the nose of the MP. By comparison, the FTEs observed by Mariner 10 (25) were only about 1 s in duration and similar in relative size to the FTEs observed at Earth, where they have typical diameters of $\sim1$ $R_E$ or about $9\%$ of the average distance to the nose of the magnetosphere. The reason for the size difference between FTEs observed by Mariner 10 and MESSENGER is not clear, but the existence of large FTEs at Mercury supports predictions that solar wind kinetic scale lengths and the small dimensions of this magnetosphere will lead to a substantial increase in the size of FTEs at Mercury relative to those at Earth (26). Overall, these MESSENGER observations suggest that magnetic reconnection at the dayside MP is very intense compared with what is found at Earth and, as a result, Mercury’s magnetosphere is probably much more sensitive to IMF intensity and direction than those of Earth.
and the other magnetized planets. The strong influence of the IMF on the magnetosphere should also serve to enhance the coupling between the solar wind and Mercury’s surface-bounded exosphere (27).

References and Notes
28. We deeply mourn the loss of our colleague and MESSENGER Co-Investigator Maria Acuña during the preparation of this manuscript; his many contributions to the MESSENGER mission and the space science community live on. We also thank all who contributed to the success of the first and second MESSENGER flybys of Mercury. Data visualization and graphics support by J. Feggans, C. Liebrecht, and M. Maroy are gratefully acknowledged. The MESSENGER project is supported by the NASA Discovery Program under contracts NASS-97271 to the Johns Hopkins University Applied Physics Laboratory and NAWW-00002 to the Carnegie Institution of Washington.

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MESSENGER Observations of Mercury’s Exosphere: Detection of Magnesium and Distribution of Constituents


Mercury is surrounded by a tenuous exosphere that is supplied primarily by the planet’s surface materials and is known to contain sodium, potassium, and calcium. Observations by the Mercury Atmospheric and Surface Composition Spectrometer during MESSENGER’s second Mercury flyby revealed the presence of neutral magnesium in the tail (anti-sunward) region of the exosphere, as well as differing spatial distributions of magnesium, calcium, and sodium atoms in both the tail and the nightside, near-planet exosphere. Analysis of these observations, supplemented by observations during the first Mercury flyby, as well as those by other MESSENGER instruments, suggests that the distinct spatial distributions arise from a combination of differences in source, transfer, and loss processes.

Whereas the interface between the planetary surface and external space environment is a classical, collision-dominated atmosphere for the three largest terrestrial planets, Mercury’s interface is a tenuous, surface-bounded exosphere in which the constituent atoms and molecules travel on collisionless trajectories and are far more likely to impact the surface than to interact with each other. Mercury’s exospheric properties are primarily determined by the interaction of the surface with the space environment. The planet’s highly elliptical orbit and proximity to the Sun lead to strong seasonal variations in exospheric density distributions (1, 2). In addition, Mercury’s intrinsic magnetic field interacts with the interplanetary medium to modulate the spatial distribution and density of solar wind plasma and high-energy charged particles that impact and sputter materials from the planet’s surface. This interaction leads to changes in exospheric densities that vary on time scales as short as a few hours (3). Impacts also supply both meteoritic and volatilized surface materials to the exosphere.

Constituents that have been detected in Mercury’s exosphere include H and He, which were measured by the Mariner 10 Ultraviolet Spectrometer (4, 5), and Na, K, and Ca, which were discovered with ground-based telescopes (6–8). Neutral species released from the surface with sufficient energy are accelerated by solar radiation pressure to form an extended, anti-sunward tail of neutral atoms, as demonstrated by ground-based observations of Mercury’s Na tail (9–11). Here, we report observations of Mg, Ca, and Na in Mercury’s exosphere and tail obtained with the Ultraviolet and Visible Spectrometer (UVVS) channel of the Mercury Atmospheric and Surface Composition Spectrometer (MASCBS) (12) on 6 October 2008 during the second Mercury flyby of the MESSENGER spacecraft (13).

Observations made by the UVVS during the first Mercury flyby on 14 January 2008 revealed a distinct north-south asymmetry (25% brighter in the north) to the Na tail and a near-planet, nightside Ca distribution with a strong dawn-dusk asymmetry (10 times brighter toward the dawn) (14). To explore these structures further, observations during the second flyby included simultaneous measurements of both of these species as well as Mg, beginning in Mercury’s tail approximately 8 R_M (R_M is Mercury’s radius, 2440 km) anti-sunward of the planet, continuing through the nightside, near-planet exosphere, and ending near the dawn terminator. The observations were restricted to narrow wavelength ranges centered on the resonant emission lines of the neutral atoms at 285.2 nm (Mg), 422.7 nm (Ca), and 589.0 and 589.6 nm (Na D2 and D1 lines, respectively). These observations confirmed the persistence of Na and Ca structures seen in the first flyby and revealed Mg in Mercury’s exosphere.

Observations of the D lines of Na began in the tail region ~56,000 km (23 R_M) behind the planet. At ~35,000 km from the planet, the UVVS switched observing programs to include the Mg and Ca resonance lines, which continued until the spacecraft was ~5000 km from the planet. Although the Na was clearly present from the beginning, the Ca and Mg emissions were detected with statistical significance only at distances less than 19,500 km (8 R_M).

During the tail observations the spacecraft rolled up and down about the Sun-Mercury line, scanning the UVVS 0.1° x 1.0° field of view across a plane defined by the Sun–Mercury line and Mercury’s north pole. As the spacecraft rotated, spectra from Mg, Ca, and Na were recorded in rapid succession along nearly identical...